Electric Energy: the Potential Showstopper for a Hydrogen Fuel-Cell Fleet

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Topics

- The Human Quest for Abundant Energy
- Competing Uses for Electric Energy
- Electric Energy for Hydrogen Production
- Future Resources for Sustainable Fuel
- Potential Solutions for Sufficient Energy

The Human Quest for Abundant Energy

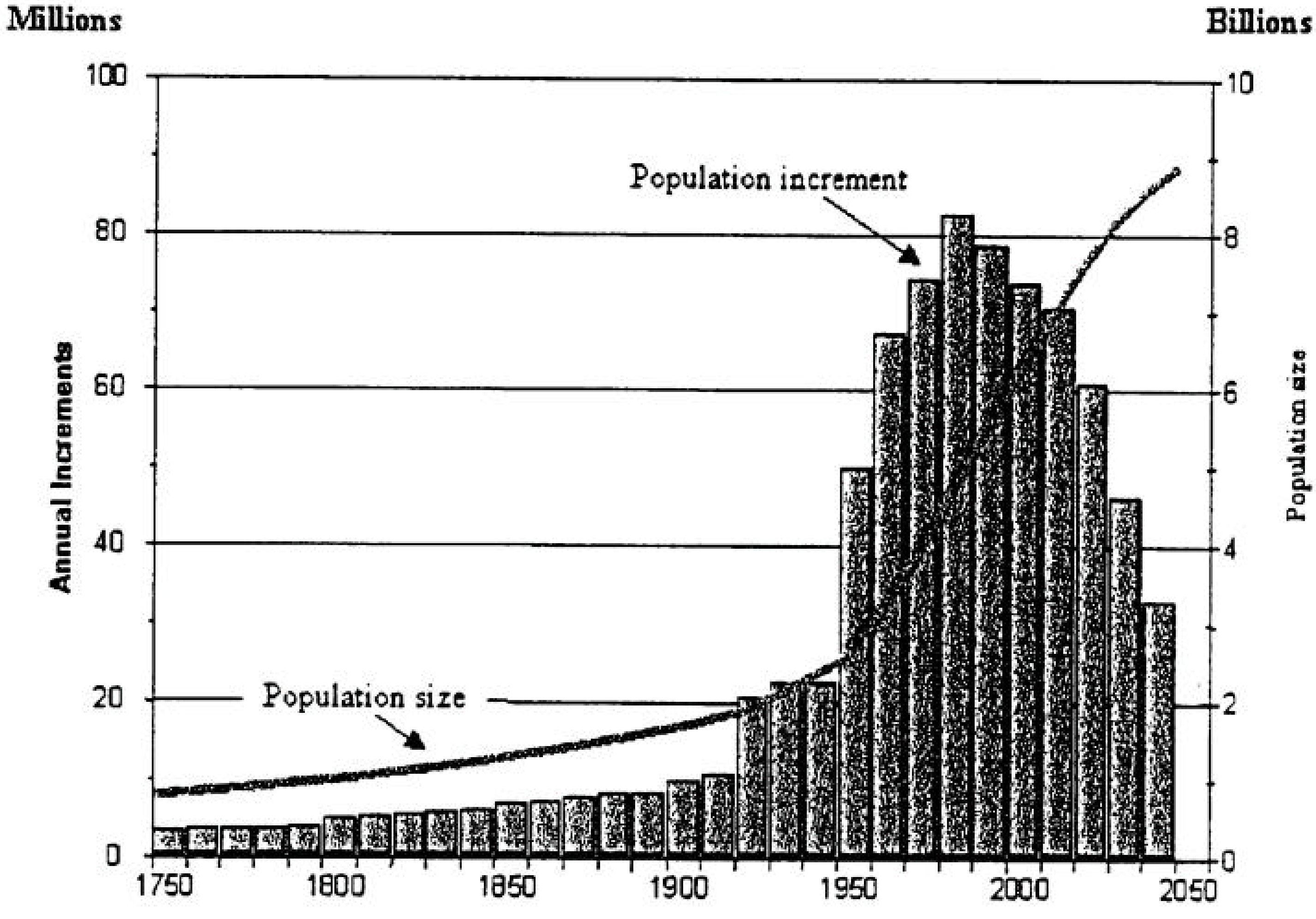
- A Philosophical Introduction

Axiom 1

- Humans have for comfort, ease, and profit historically progressed in energy sources
- from humans (self, family, slaves, employees)
- to animals (camels, oxen, horses)
- to machines (water, steam, electricity, radiation)
- at continuously increasing consumption of energy per unit of useful work.
- Therefore, at any given growth rate of human population, total energy consumption will grow at a greater rate.

The World at Six Billion

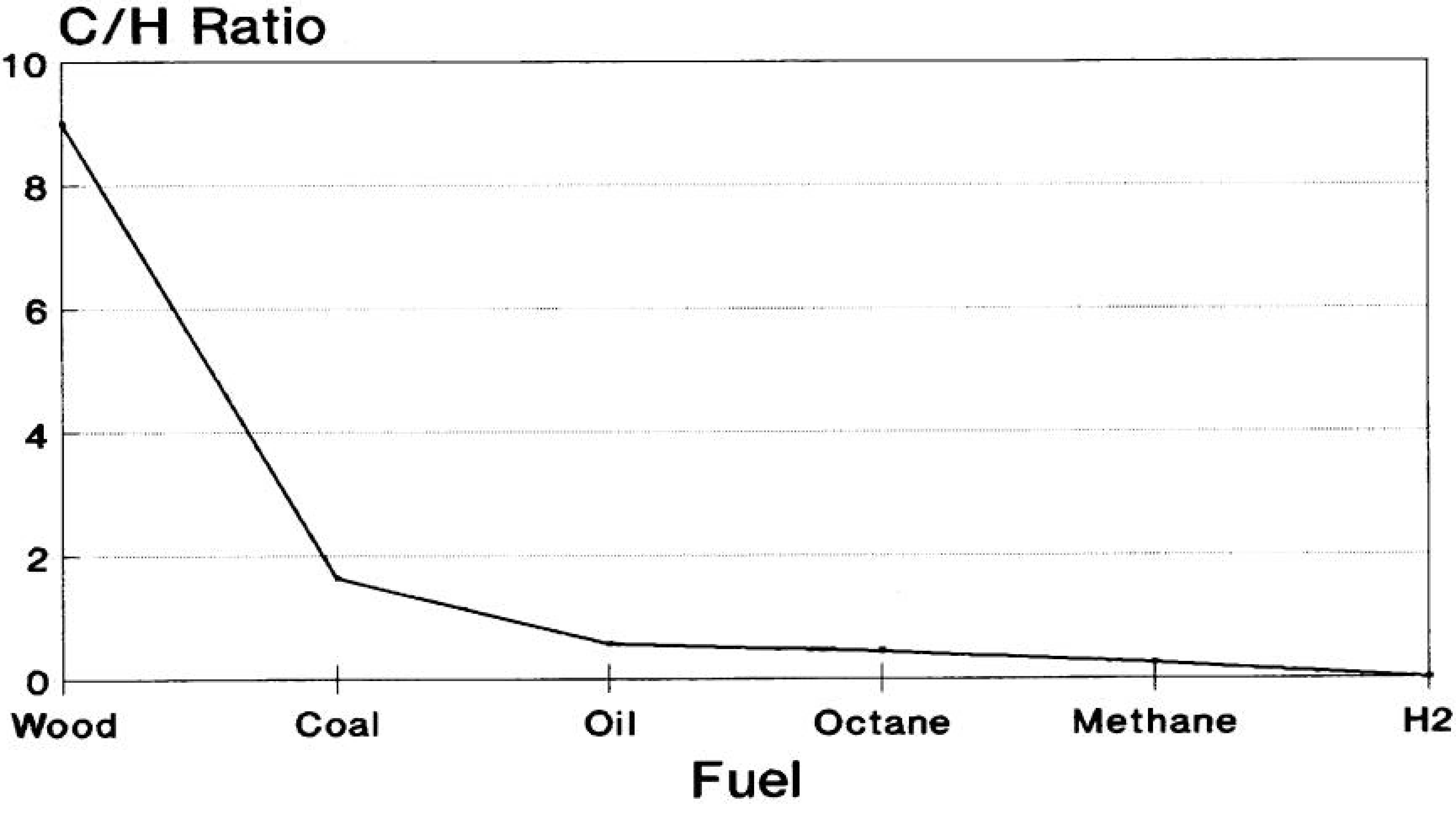
United Nations Population Division



Axiom 2

- Fundamental human goals include the desire for
- 1. “Pleasant Habitat”
- a clean and safe environment
- 2. “comfort and Ease”
- abundant energy on demand

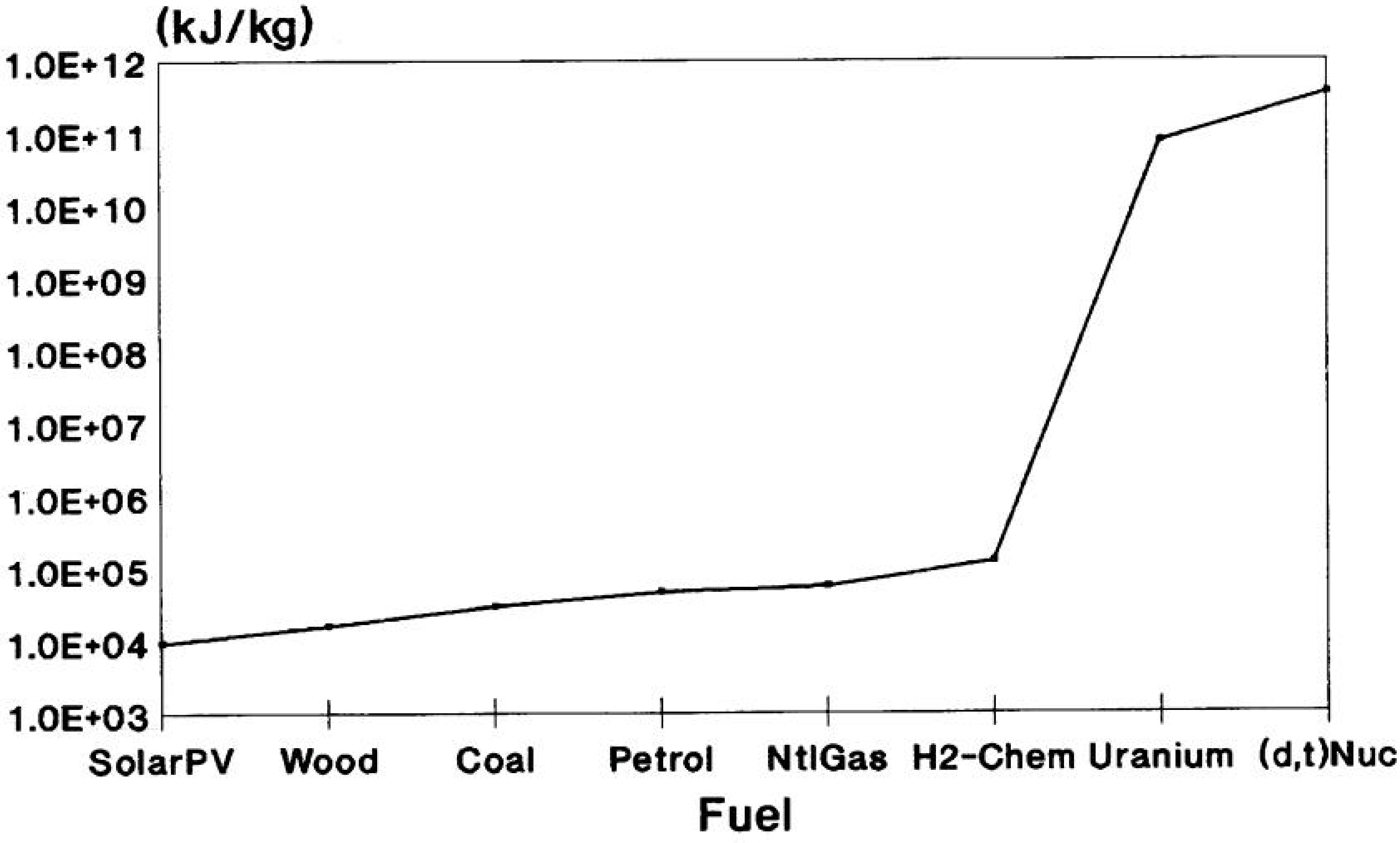
The Quest for Clean Fuel



Axiom 3

- The history (and future) of Humanity follows a One Way and Irreversible Path

Specific Energy of Fuel



Are We Losing Our Way in This Quest?

- Will energy consumption continue to grow at a greater rate than population?
- Will the goals of a clean and safe environment and abundant energy on demand be abandoned?
- Will human history continue in an irreversible path?

The Technology Question

- As population continues to grow, should we try to reverse the quest for greater specific energy technology?

The Social Question

- As population continues to grow,
- Do We Regress (Do Without)?
- or
- Do We Advance(Do Better)?

Future Electricity Demand

Business-as-Usual Growth

$$\Delta ED = \int_{now}^{later} (B.a.U.)\, e^{g \cdot dt} - \int_{now}^{later} \text{Conservation}\, e^{c \cdot dt}$$

Plus Large Incremental Additions

- New Transportation Fuel: Hydrogen
- Electronic Way of Life
- Crosscontinental Superconducting Grid

The Electronic Way of Life

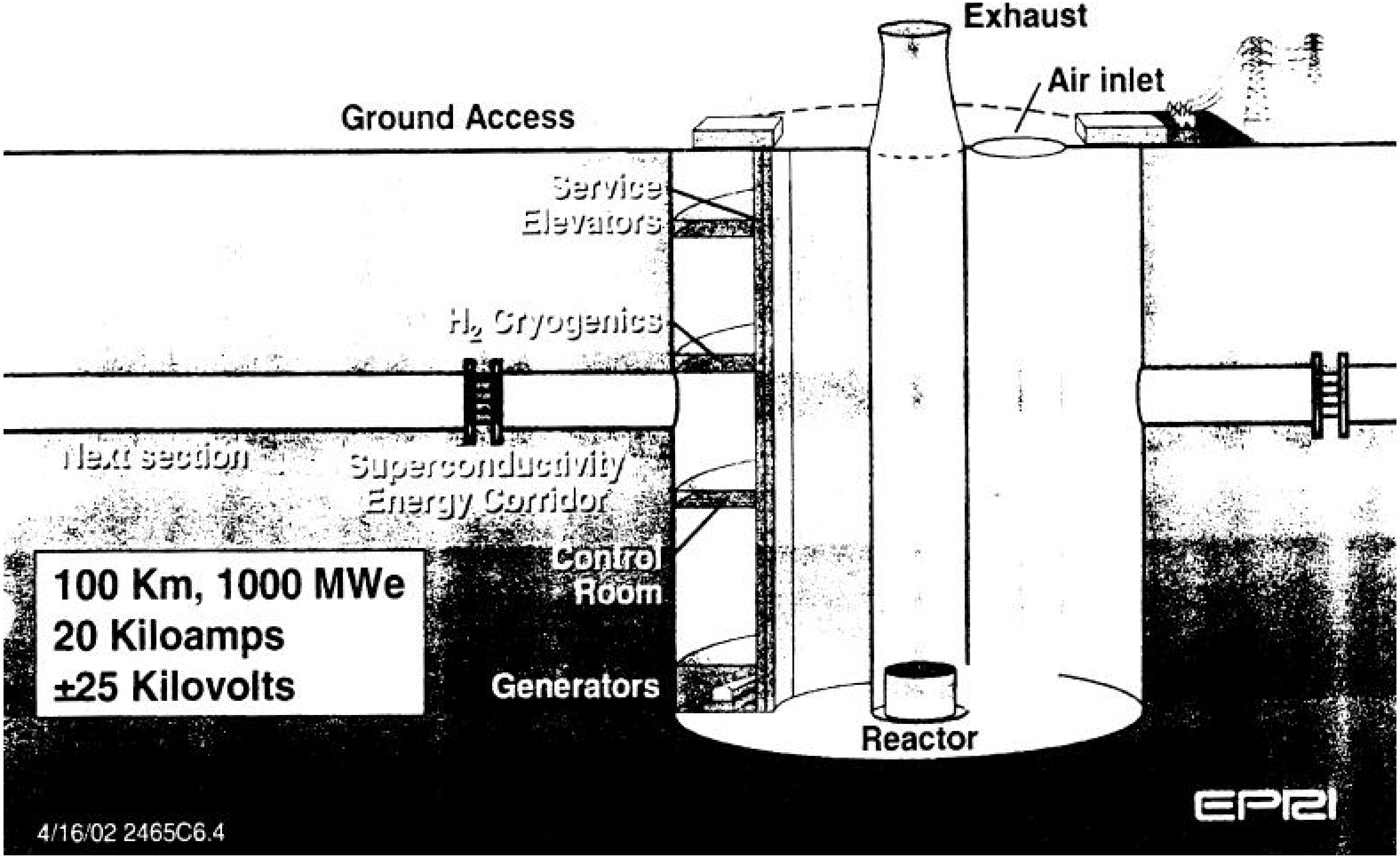
- Future exponential growth of electric energy demand for
- Computers
- Mobile cell phones
- Home management
- Information technology
- Aviation security
- Homeland defense

Continental Superconducting Grid

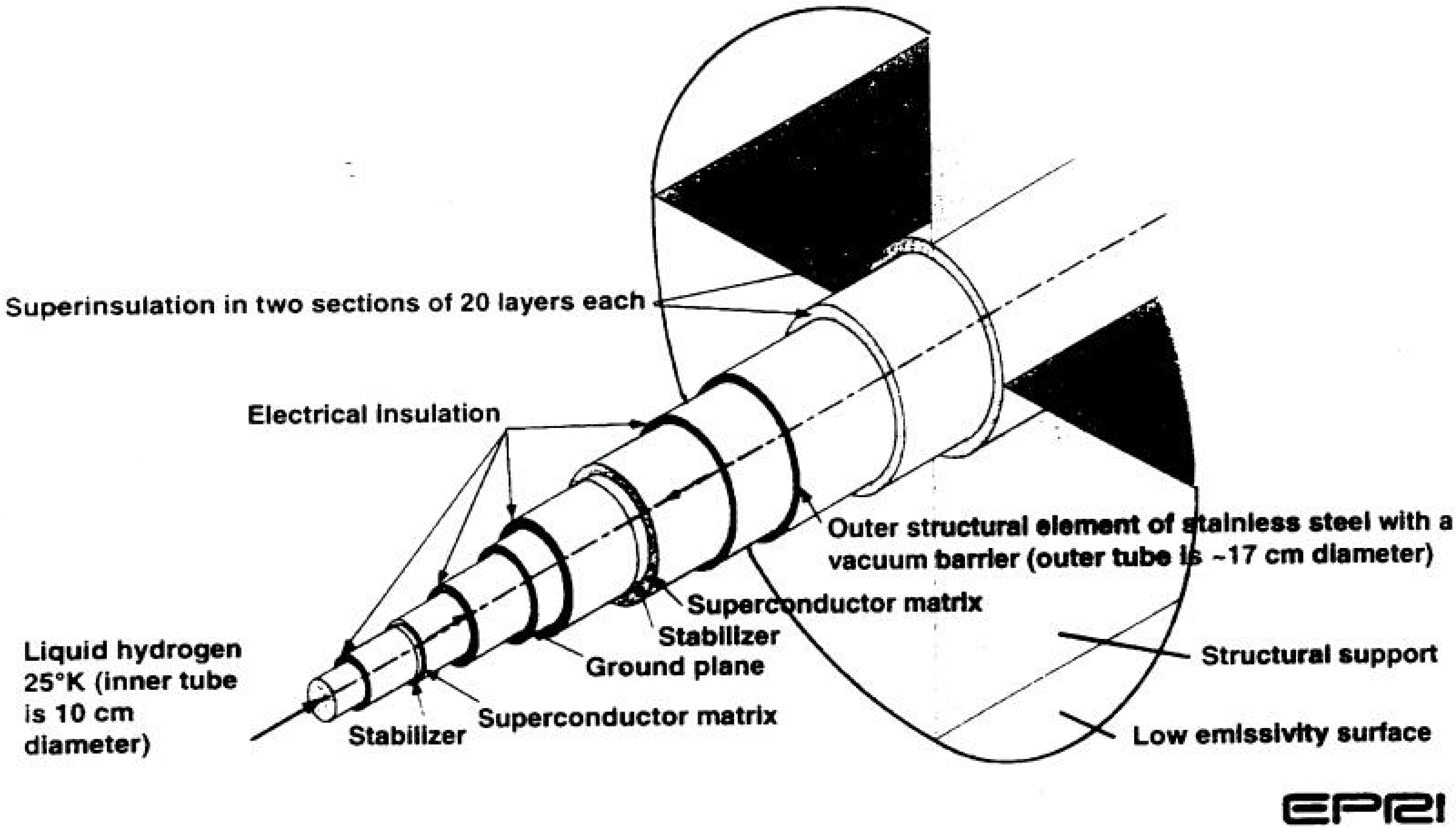
Courtesy: Chauncey Starr, EPRI

- **Concept**
- Coast-to coast transmission corridor
- ‘low-cost’ $MgBr_2$ superconductor cooled by LH_2
- Power plants along corridor produce electricity and LH_2
- Local branches deliver both electricity and GH_2
- **Advantages**
- Supplements regional electric power grids
- Provides load diversity across 4 time zones
- Renewable + nuclear energy = sustainable power
- “spent” coolant hydrogen available locally as hydrogen fuel

Supergrid Section



$MgBr_2$ DC Superconductor Line



Electric Energy Requirement for Large-Scale Production of Hydrogen Fuel

HFleet Scenario Model

HFleet Scenario Model

- Extrapolation of historic population, vehicle transportation, and electricity data in a dynamic model in two time stages:
- 2000-2010, when a fuel-cell vehicle industry is likely to expand rapidly
- 2010-2050, when a large fraction of the fleet could operate with hydrogen fuel

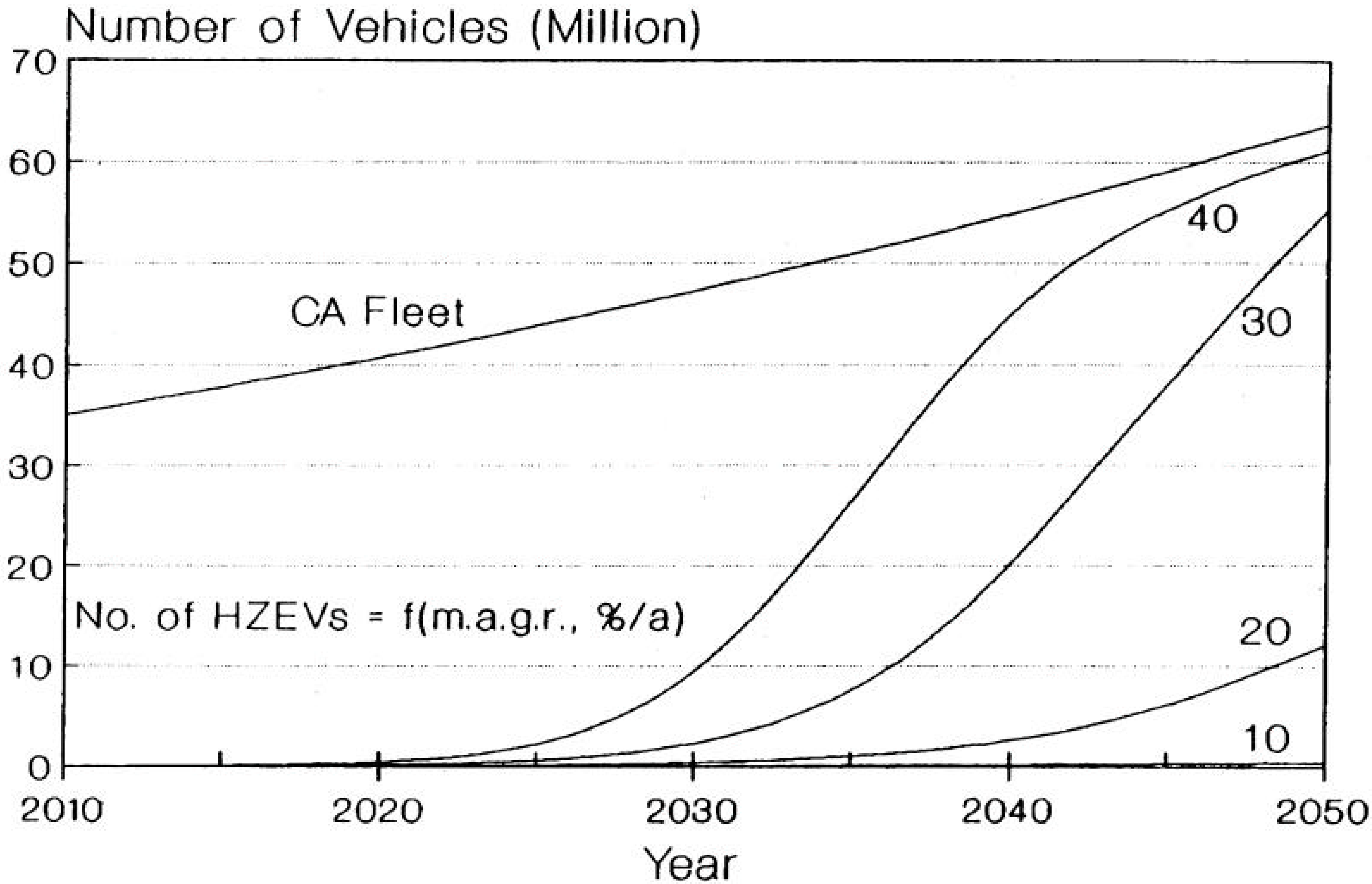
Details of Methodology and Data

- **Air Quality Aspects**
- 11th World Hydrogen Energy Conf., I.A.H.E., Stuttgart, Germany, 1966
- **Potential Air Quality Improvement, Tokyo (WE-NET)**
- 12th World Hydrogen Energy Conf., I.A.H.E., Buenos Aires, Argentina, 1998
- **Electric Power Study for California**
- International J. Hydrogen Energy, Vol. 25, May 2000
- **Electric Power Study for the United States**
- International J. Hydrogen Energy, Vol. 25, Nov 2000
- **Electric Power Study for the World Vehicle Fleet**
- International J. Hydrogen Energy, Vol. 26, Nov 2001

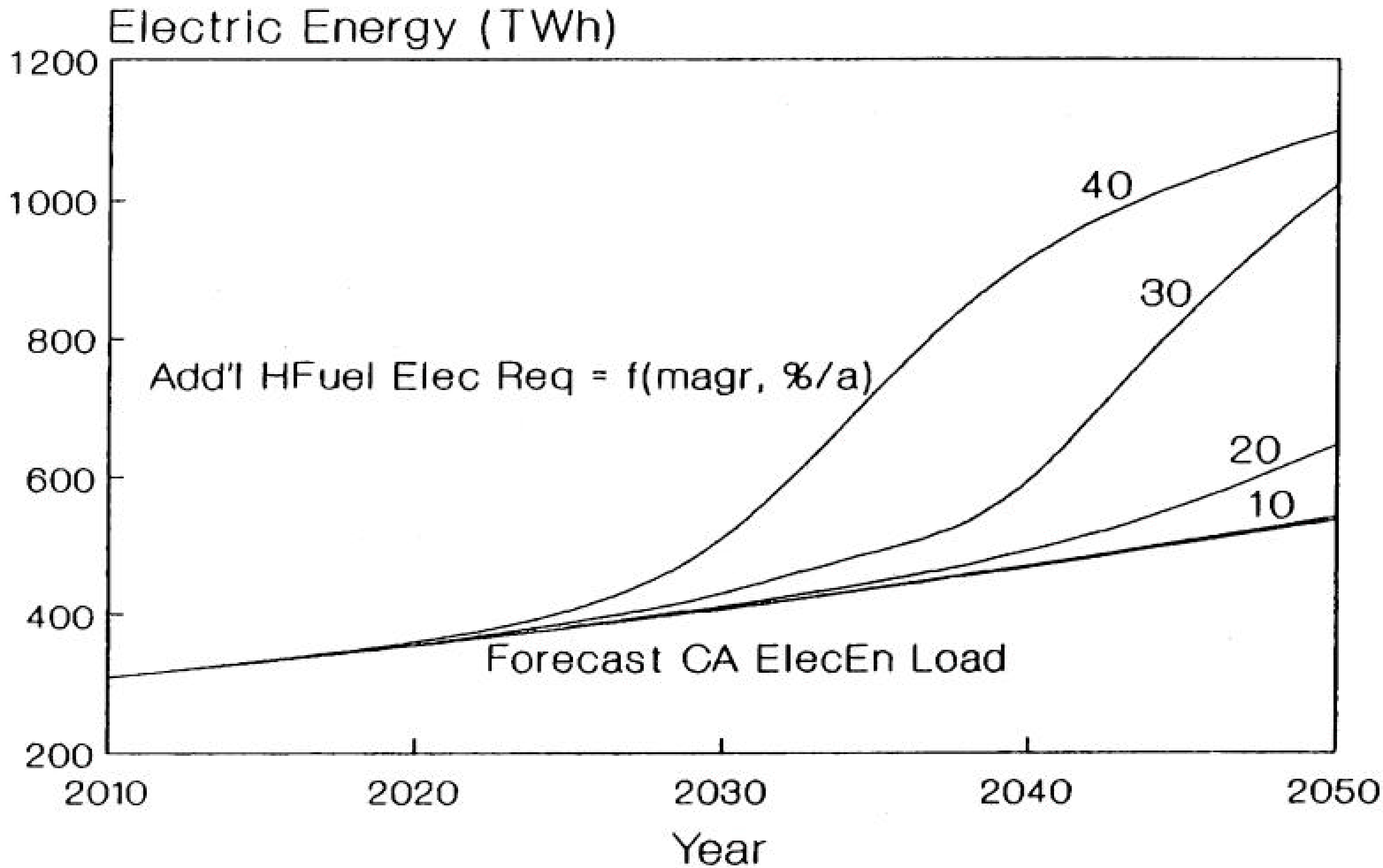
Results: B.a.U. 1990-2010

	Calif.	U.S.	World
Population (10^6)			
1990	29.8	251	5290
2000	34.9	276	6060
m.a.g.r.(%/a)	1.60	0.96	1.36
2010	40.9	304	6940
Vehicle Fleet			
1990	25.5	184	566
2000	29.9	229	715
m.a.g.r.(%/a)	1.60	2.19	2.33
2010	35.1	243	902
Affluence (?) (VpC)			
1990	0.857	0.78	0.11
2010	0.863	0.80	0.13
Electricity Demand (PWh)			
1990	0.229	2.97	11.7
2000	0.266	3.80	15.1
m.a.g.r.(%/a)	1.49	2.48	2.50
2010	0.309	4.85	19.3

California Vehicle Fleet

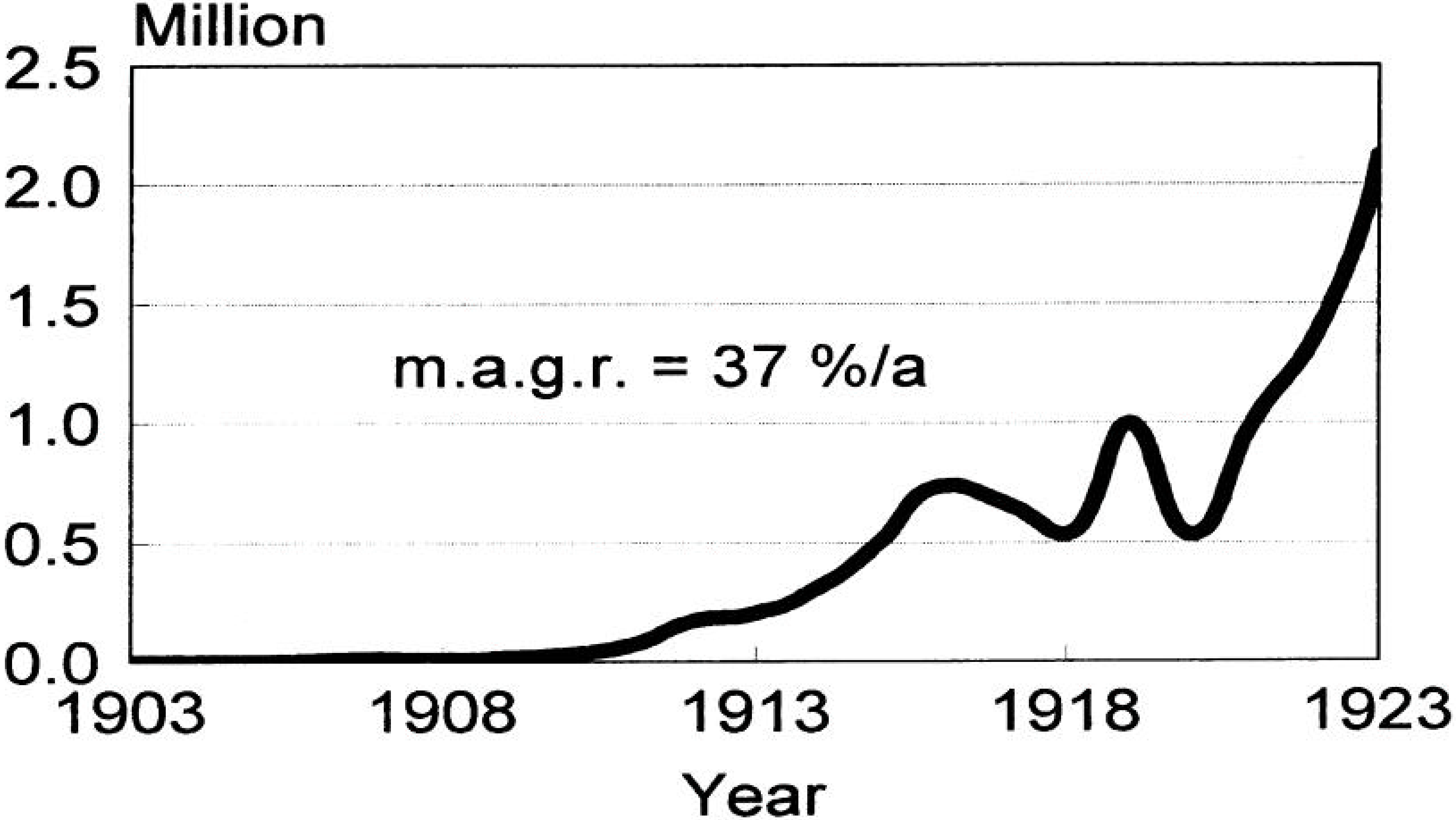


CA HFuel Electric Energy Req.

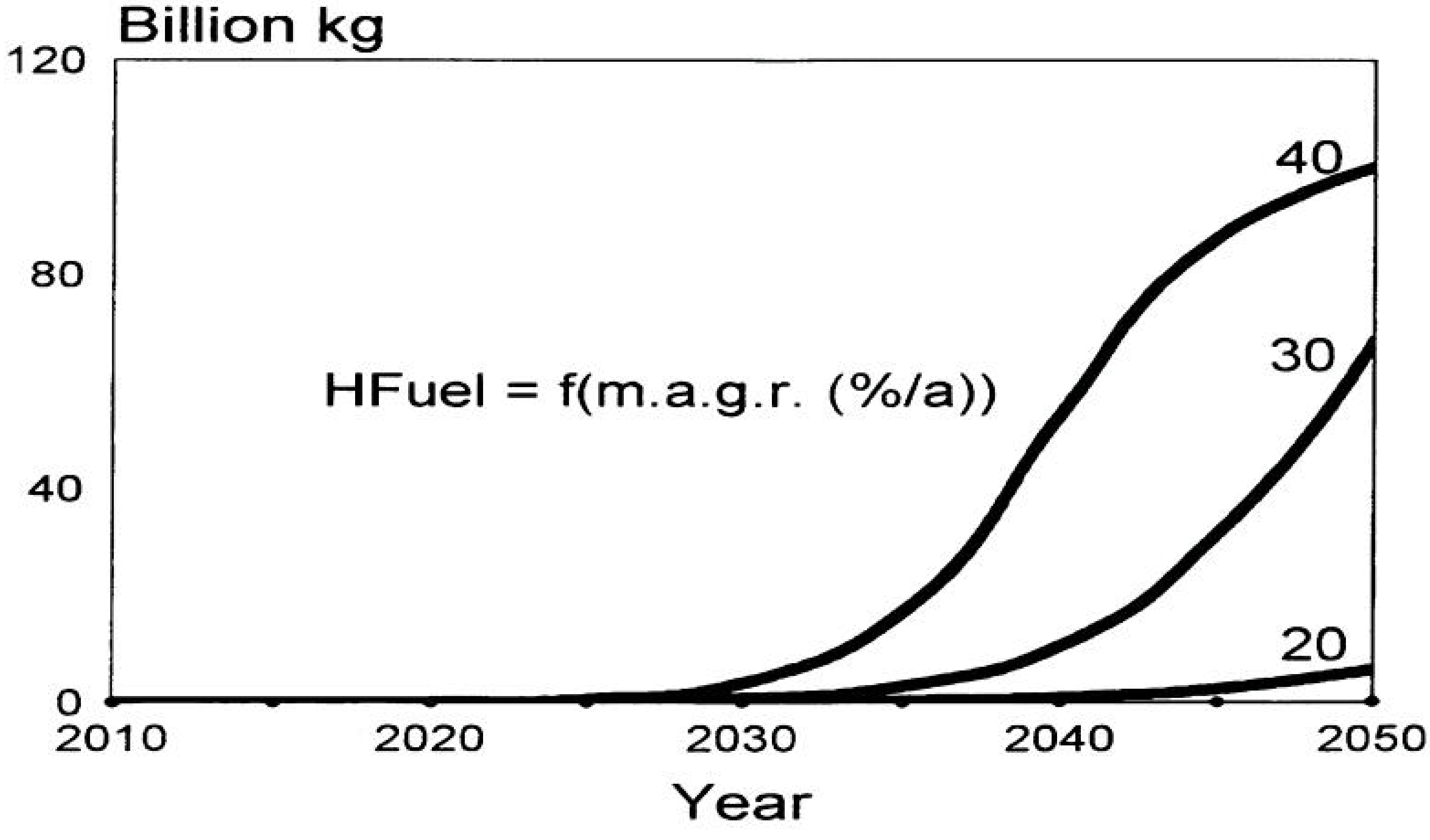


Ford Motor Co. Production

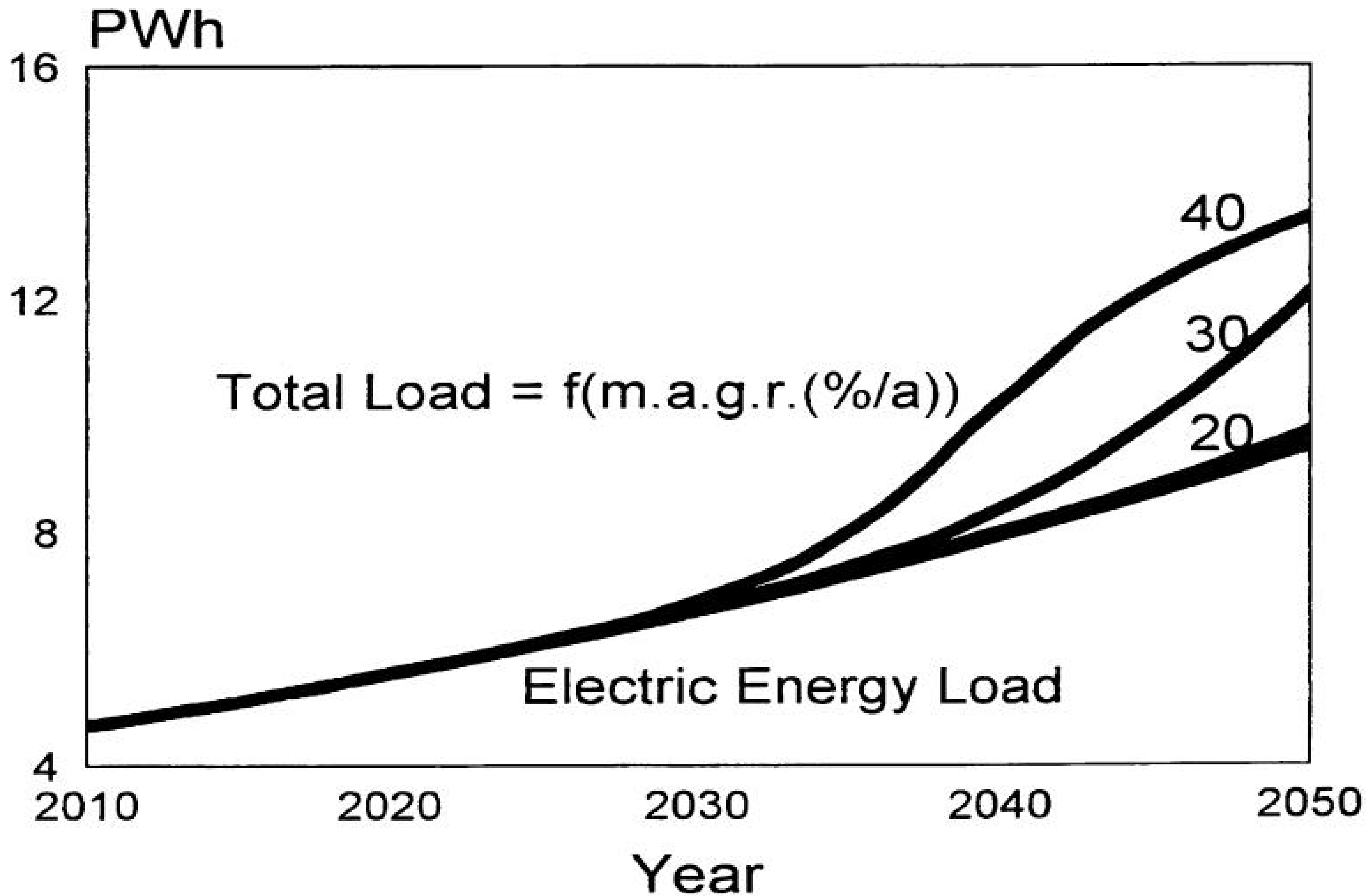
1903-1923



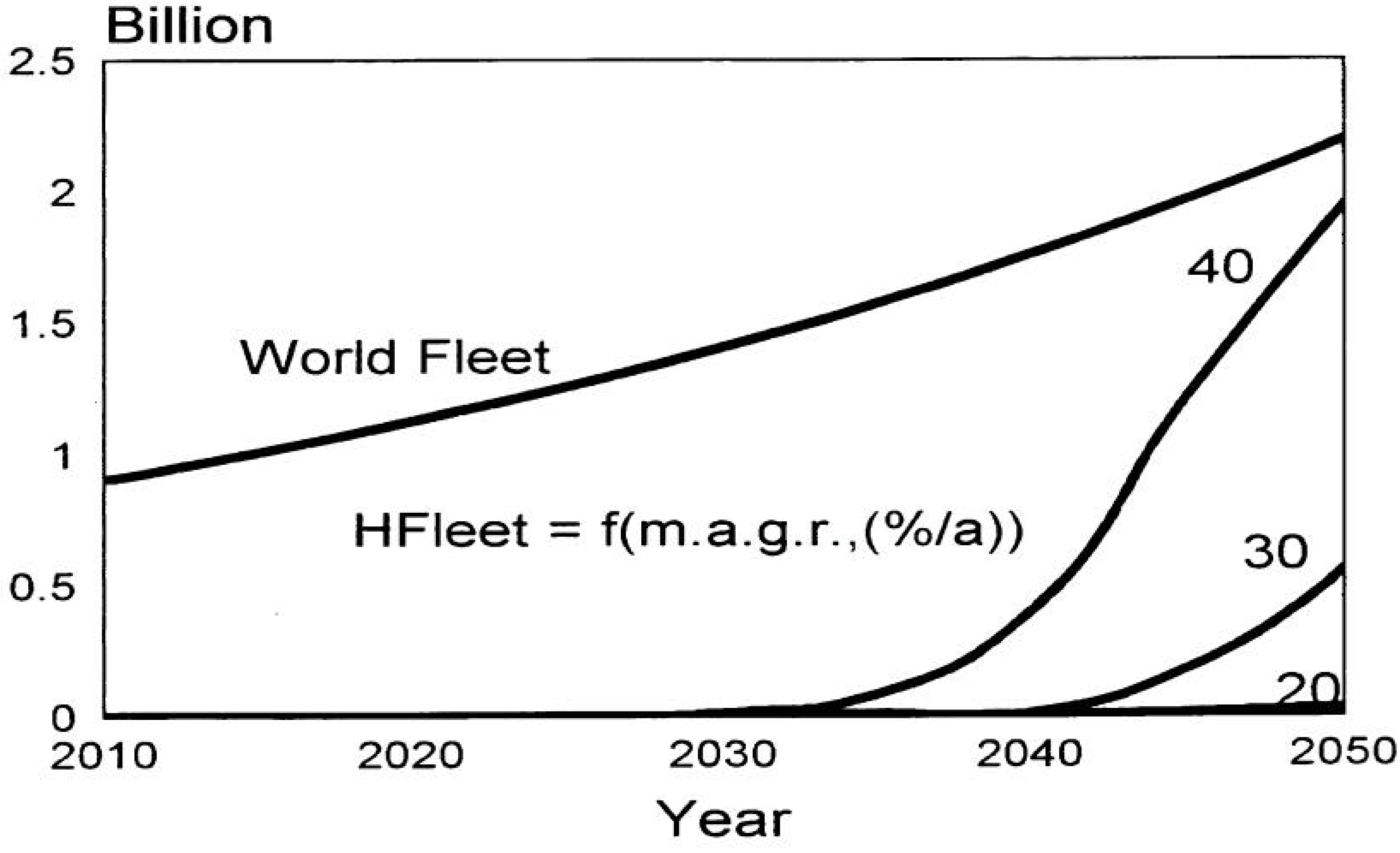
U.S. HFuel Requirement



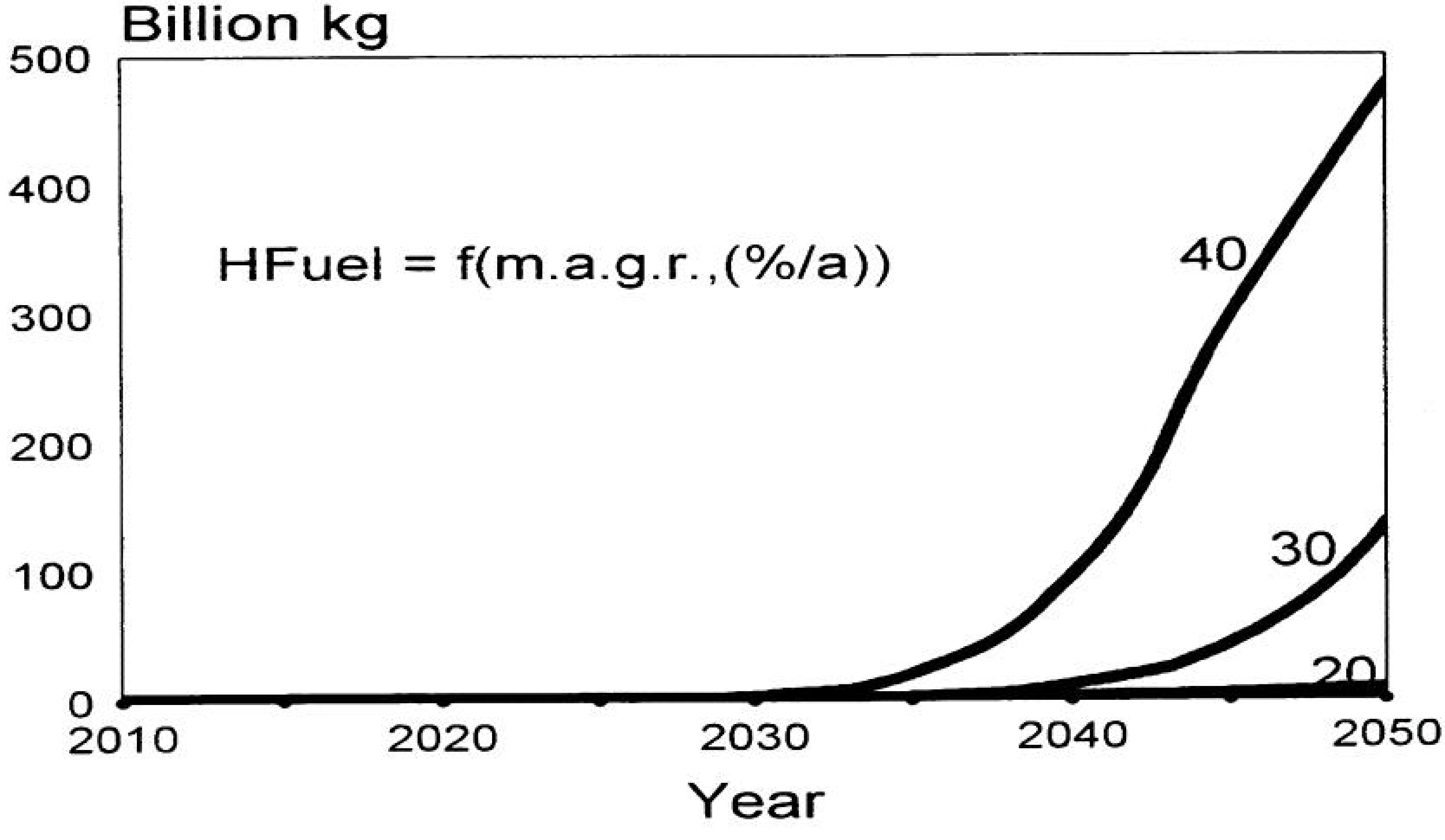
U.S. HFuel Electric Energy Req.



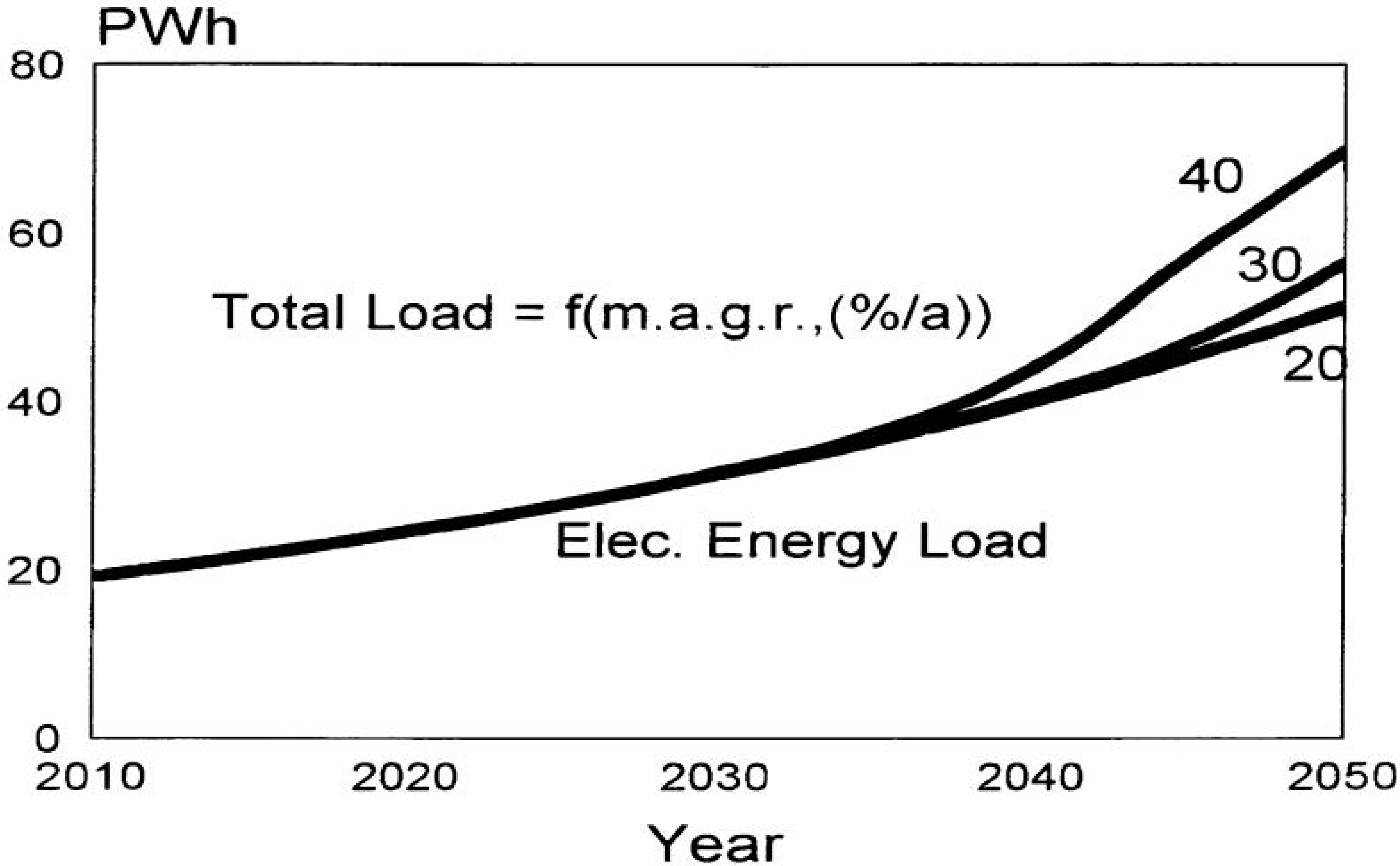
World Vehicle Fleet



World HFuel Requirement



World HFuel Electric Energy Req.



Results: 2010-2050 Scenarios

	Calif.	U.S.	World
Population (10^6)			
2010	40.9	304	6940
2050	~ 75	~ 450	~ 9000
Vehicle Fleet (10^6)			
2010	35.1	243	902
2050	63.7	458	2200
HFleet (10^6)(@40%/a)			
2010	0.00	0.00	0.00
2050	61.2	437	1950
HFuel (10^9 kg)			
2010	0.00	0.00	0.00
2050	1.25	99	477
Electricity (PWh)			
2010	0.31	4.85	19.3
2050 (B.a.U)	0.54	8.16	51.1
2050 (w/HFuel)	1.08	11.6	69.8

Natural Gas for Transportation

NG vs. H_2 as an Automotive Fuel

	Spec.En. (kWh/kg)	Vol.En. (kWh/Nm^3)
Compressed (CNG)	13.9	3.38
Liquid (LNG)	13.9	5.8
Compressed (CH_2)	33.3	0.64
Liquid (LH_2)	33.3	2.36

Natural Gas to Produce Hydrogen Fuel

Commercial Process

Reforming: $CH_4 + H_2O \rightarrow 3H_2 + CO$

'Shift': $\underline{CO + H_2O \rightarrow H_2 + CO_2}$

Overall: $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$

Molar Mass: 16 kg CH_4 $\rightarrow$ 8 kg H_2

Combustion Energy

	CH_4	H_2
Specific En.(kWh/kg)	13.9	33.3
Molar Heat (kWh)	222	266

Competing Uses for Natural Gas

- Petrochemical for chemical synthesis
- Combustible fuel for residential and industrial heating/cooling
- Combustible fuel for electric power generation
- Reformer feed for hydrogen production

Long-Term Sustainability for Natural Gas in the U.S.

Demand for Natural Gas to 2050
(Tcuft)

	2000*	2020*	magr (%/a)	2050**
Comm./Ind.[a]	13.6	17.4	(1.2)	25.1
Residential	5.0	6.0	(0.9)	7.9
Transportation (CNG)	0.02	0.14	(9.8)	2.6
Utility Electric Power	4.2	10.3	(4.5)	40.0
Hydrogen Production[b]	0.0	0.03	(2.2)	19.5
Total Demand	22.8	33.8	(3.4)	95.1
Forecast Supply*	22.7	34.1	(2.1)	64.4

* adapted from DOE/EIA (AEO-2002)
** extrapolated at constant m.a.g.r.
(a) includes use as petrochemical feedstock
(b) all by steam reforming; none by electrolysis

Potential Distribution of Energy Resources for HFuel Production in the U.S.

Year	Forecast Demand EIA/DOE* (PWh)	Forecast Demand Model (PWh)	Forecast Renewables (PWh) (%)	Fossil Fuels (Pwh) (%)	On-Line Nuclear (PWh) (%)
1999	3.39	--	0.35 (10%)	2.31 (68%)	0.73 (22%)
2010	4.22	4.68	0.39 (9%)	3.11 (74%)	0.72 (17%)
2020	4.87	5.59	0.40 (8%)	3.90 (80%)	0.57 (12%)
m.a.g.r. (%/a)	+1.7	+1.8	+0.5	+2.5	- 1.1
2050**	n/a	13.4	5.36 (40%)	X	0.41 (3%) +Y

Shortfall could be alleviated within the range

X (%)	+	Y (%)	(No.NPP)
8.0 (57)		0 (0)	0
4.0 (30)		4.0 (27)	400
0 (0)		8.0 (57)	800

* adapted from Table A8,p.139, "Annual Energy Outlook 2001 with Projections to 2020", DOE/EIA-0383(01), December 2000

** for study, total energy required = 9.5 (w/o H_2 production) + 3.9 (w/ H_2)

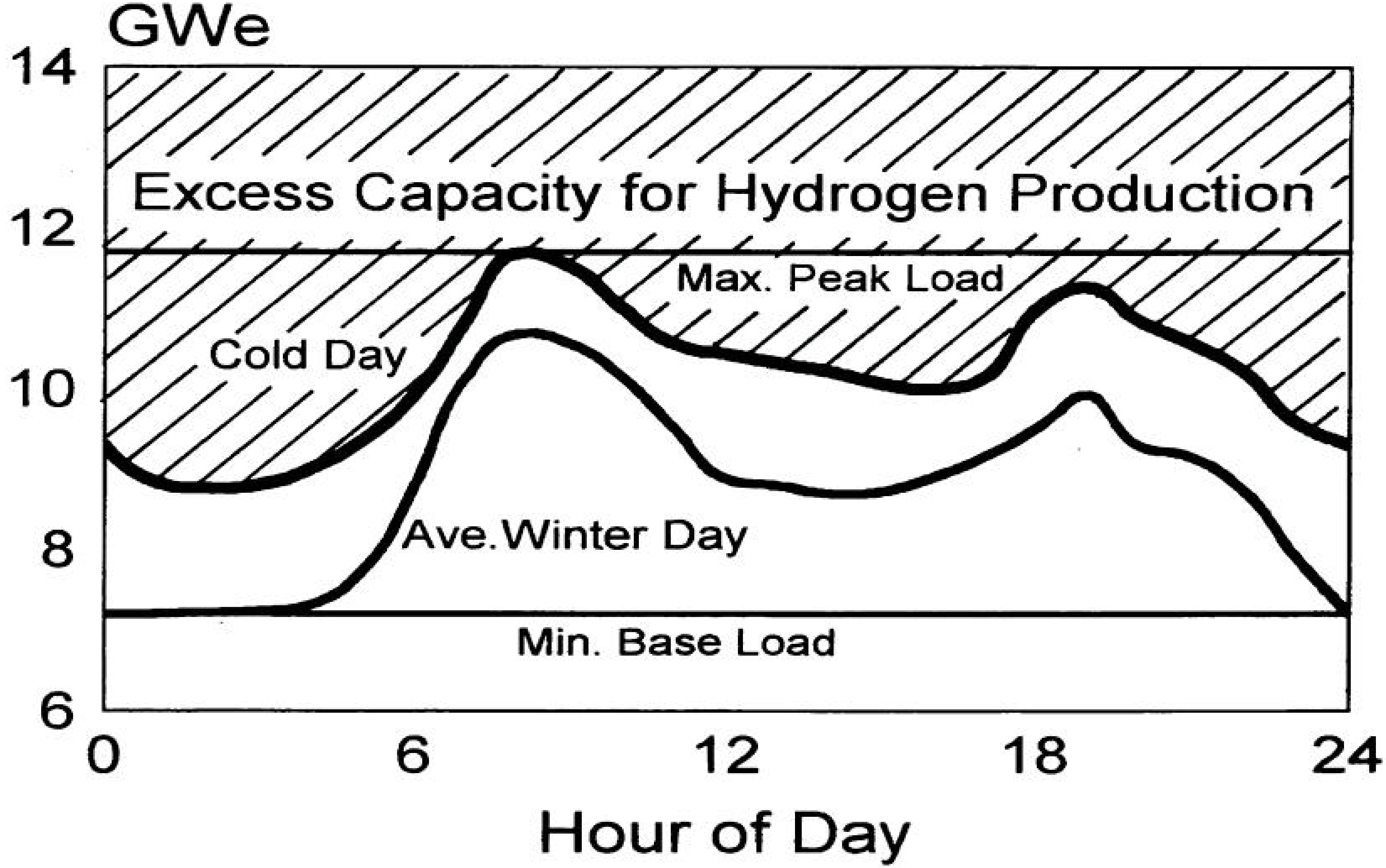
Potential Distribution of Energy Resources for World HFuel Production

	Forecast Demand		Forecast Renewables		Fossil Fuels		On-Line Nuclear	
	EIA	IAEA						
Year	(PWh)	(PWh)	(PWh)	(%)	(PWh)	(%)	(PWh)	(%)
1997	12.3	14.9('99)	2.61	(21.3)	7.37	(60.0)	2.28	(18.6)
2010	16.8	18.3	3.57	(21.2)	10.79	(64.1)	2.46	(14.6)
2020	21.6	22.3	4.31	(21.0)	15.13	(70.1)	2.14	(9.9)
m.a.g.r. (%/a)	2.46	1.91	2.18		3.13		−1.39	
2050	51.1		20.5	(40.0)	X		1.41 (2.8) + Y	

Potential Distribution of Additional Energy Shortfall

X	(%)	+	Y	(%)	No.NPP
29.2	(56.8)		0	(0)	0
19.6	(28.4)		19.6	(28.4)	1960
0	(0)		29.2	(56.8)	2920

Dual-Purpose Electric Power Plant



Solar-Nuclear-Hydrogen Energy Parks

- **Concept**:
- Large-area industrial park in remote solar area with
- central cluster of nuclear power plants surrounded by
- field of photovoltaic cells and wind power mills
- **Synergistic Coupling**
- Reduced problems of alternate energy sources
-     Nuclear: unpopularity of high-specific energy
-     Solar: technical problems of low-specific energy
- Increased efficiency for electricity/hydrogen production
-         Dual-purpose power plants
-         Preheating for higher-temperature electrolysis